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(בעברית) (Hebrew) גלאי פולשים על ידי לייזר

(באנגלית) (English) Laser Intruder Detector

מבקש בזאת כי ינתן לי עליה פטנט
hereby apply for a patent to be granted to me in respect thereof.

* בקשת חלוקה – Application of Division	* בקשת פטנט מוסף – Application for Patent Addition	* דרישה דין קדימה Priority Claim		
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גלאי פולשים על ידי לייזר

Laser Intruder Detector

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LASER INTRUDER DETECTOR

FIELD OF THE INVENTION

The present invention relates to intruder detection systems and in particular to the detection of intruders using lasers.

BACKGROUND OF THE INVENTION

Intruder detection systems for detecting the presence and movement of an intruder in an area or volume of space, hereinafter referred to as a "surveillance zone", are well known in the art. Such systems are used for example to protect homes and businesses from unauthorized entry and in less sinister applications to detect an individual's presence in a room.

Various different types of intruder detection systems exist and they employ different technologies to detect an intruder. Common among these detection systems are different types of active and passive infrared (PIR) detection systems, systems that use microwaves for detection and systems that use acoustic waves. Less common, are intruder detection systems using laser light.

All of the various detection systems have to contend with providing high efficiency for detecting an intruder while providing a low rate of false alarms (*i.e.* a low rate of "detecting" intruders that are not there). Generally as components in a detection system provide higher sensitivity for detecting changes in a surveillance zone caused by an intruder, the system has to provide more sophisticated and complicated stratagems to prevent false alarms and assure reliable system operation.

For example, PIR detection systems are particularly sensitive to changes in sensitivity of IR detectors caused by changes in ambient temperature and these systems are generally designed with means for adjusting system components responsive to these changes. The ability of an IR detection system to detect an intruder is also often affected by what the intruder wears and how the intruder moves in a surveillance zone protected by the system. Radio frequency (RF) detection systems, while not particularly sensitive to ambient temperature, have to contend with RF background noise from a plethora of devices and appliances that can interfere with reliable operation. Similarly, acoustic systems generally operate in noisy environments that can affect the reliability with which these systems operate. Often intruder detection systems use two different types of detection technologies in order to reduce false alarms and improve system reliability.

A PIR detection system is described in US Patent 5,629,676 to Kartoun, et al. The system comprises a temperature sensor and adjusts a detection threshold of components in the system responsive to changes in ambient temperature. A "dual" detection system is described in

US Patent 5,684,458 to Calvarese. A detection system described in this patent comprises both an RF Doppler detection subsystem and a PIR detection subsystem. An alarm is raised indicating an intruder only when the RF detection subsystem and the PIR subsystem simultaneously indicate the presence of an intruder.

A laser detection system described in US patent 5,910,767 to Frucht uses a laser beam to continuously scan a surveillance zone. Reflectivities with which objects and features in the surveillance zone reflect light from the laser beam and distances to the features and objects are measured using the laser beam and stored. During subsequent scans with the laser beam, distances to the objects and features and reflectivities with which they reflect laser light are compared to the stored distances and reflectivities and analyzed to determine whether or not an intruder is present in the surveillance zone. Scanning is accomplished by mechanically rotating a mirror that reflects the laser beam into the surveillance zone. The system should be relatively immune from changes in the ambient environment and from either RF or acoustic noise. However, the system requires relatively accurate monitoring and control of mechanical components that rotate the laser beam and relatively complicated algorithms for storing and analyzing distance data from the surveillance zone. In addition, because of the moving mechanical parts, the system most probably requires relatively frequent maintenance and is relatively expensive to produce.

The use of Doppler shifting, and Doppler shifting of light for detecting motion is well known in the art. US Patent 4,611,912 to Falk describes a method and apparatus for optically measuring velocity of an object and distance to the object. The velocity is determined by measuring the amount by which the velocity of the object Doppler-shifts light from a laser diode.

SUMMARY OF THE INVENTION

An aspect of some preferred embodiments of the present invention relates to providing an improved intruder detection system that provides high detection efficiency and low false alarm rate and that is relatively inexpensive and simple to produce and maintain.

An aspect of some preferred embodiments of the present invention relates to providing a detection system comprising a plurality of in-phase laser beams that simultaneously illuminate different portions of a surveillance zone. If movement is detected in one or more of the laser beams, a signal is generated indicating the intruder's presence.

According to an aspect of some preferred embodiments of the present invention Doppler shifts in the frequency of light reflected from a laser beam of the plurality of laser beams, by an intruder moving in the surveillance zone, are used to detect the intruder.

An intruder detection system, in accordance with a preferred embodiment of the present invention comprises a laser and a plurality of photo-detectors sensitive to light radiated by the laser. Light from the laser is incident on a means for diffracting light, hereinafter referred to as a "diffractor", such as diffraction grating or suitable holographic diffraction plate. Preferably, most of the laser light that is incident on the diffractor is forward-diffracted into a plurality of laser beams, hereinafter referred to as "sensor beams". The sensor beams spread out from the diffractor and extend into different regions of the volume of a surveillance zone protected by the intruder system. Preferably a small portion of the incident laser light is back-diffracted by the diffractor into one or more beams, and preferably a plurality of beams, hereinafter referred to as "reference beams". Each reference beam is preferably focused on a different one of the plurality of photo-detectors, for example by an appropriate lens.

If a sensor beam illuminates an intruder present and moving in the surveillance zone, light from the sensor beam is reflected back to the diffractor. Some of the reflected light is diffracted by the diffractor onto one or more of the photodetectors. Each of the photo-detectors generates an output signal responsive to both reference beam light and light reflected from the sensor beam that is incident on the photo-sensor. However, the frequency of the reflected light is generally Doppler shifted by the movement of the intruder. As a result, the output signal from each photo-detectors has a signal component, hereinafter referred to as a "Doppler signal" characterized by the Doppler shift frequency, which Doppler shift frequency is determined from the Doppler signal using methods known in the art. If a determined Doppler shift frequency has a value that lies within a range of values that are indicative of the motion of an intruder, and is characteristic of intruder motion, the detection system generates an output signal indicating an intruder's presence.

In some preferred embodiments of the present invention, a particular value for a Doppler shift frequency is not determined or required in order for the intruder detection system to generate an output signal indicating an intruder's presence. An output signal is generated if an amount of energy in output signals from photo-detectors, is greater than a predetermined minimum threshold quantity of energy in a band of frequencies characteristic of Doppler shift frequencies caused by an intruder. Depending upon the purpose for which the intruder system is being used, the output signal indicating the intruder's presence may, for example, generate an alarm, turn on an appliance or open a door - or just wish the intruder a nice day.

According to an aspect of some preferred embodiments of the present invention light reflected by an intruder from a sensor beam illuminating the surveillance zone is used to determine a direction of motion of the intruder in the surveillance zone.

In some preferred embodiments of the present invention, the diffractor is mechanically vibrated back and forth in a direction perpendicular to the plane of the diffractor. This Doppler shifts the frequency of the reference beams by an "offset Doppler-shift" that depends upon the velocity of the diffractor. When a photo-detector receives light reflected from a sensor beam by a moving intruder (or object) it generates a Doppler signal having a Doppler frequency that is the sum of the offset Doppler frequency and a Doppler shift frequency caused in the reflected light by the intruder's motion. If the Doppler frequency of the Doppler signal is greater than the offset Doppler shift, the intruder is moving with a component of velocity in the direction of motion of the diffractor. If the Doppler frequency of the Doppler signal is less than the offset Doppler shift, the intruder is moving with a component of velocity in a direction opposite to the direction of motion of the diffractor. As a result, the direction of motion of the intruder can be determined, in accordance with a preferred embodiment of the present invention, from the Doppler frequency of the photo-detector Doppler signal and the direction of motion of the diffractor.

In some preferred embodiments of the present invention, the direction of motion of the intruder is determined by introducing a time dependent phase shift into light reflected by an intruder. The time dependent phase shift appears as a frequency shift in intruder reflected light that generates a beat frequency between reference beam light and intruder reflected light. The beat frequency is increased or decreased depending upon the direction of motion of the intruder. For example, if the time dependent frequency shift increases the frequency of intruder reflected light and the intruder is moving towards or away from the source of the sensor beams the beat frequency will respectively increase or decrease. Methods for introducing time dependent phase shifts in light are known in the art. For example, a time dependent phase shift can be introduced into intruder reflected light by passing sensor beam light and intruder reflected light through a plate of piezoelectric material whose optical length is controlled by an electric field.

In some preferred embodiments of the present invention, quadrature detection is used to determine the direction of motion of an intruder. Reflected sensor light from an intruder passes through a linear polarizer and quarter wave plate so that it becomes circularly polarized. The circularly polarized reflected light is filtered through a first polarizer having its polarization axis along a first direction and focused on a first photo-detector of the plurality of photo-detectors. The circularly polarized reflected light is also filtered through a second polarizer having its polarization axis along a second direction and focused on a second photodetector of the plurality of photo-detectors. The first and second polarization directions are perpendicular

to each other. As a result, reflected light reaching the first photo-detector is 90^o out of phase with respect to that reaching the second photo-detector. The Doppler signals from the first and second photo-detectors are therefore 90^o out of phase with respect to each other and function as a pair of "Doppler quadrature signals". One of the quadrature signals leads the other. Which one leads depends upon whether the frequency of the reflected sensor beam light is Doppler shifted up or down, which of course depends upon the direction of motion of the intruder. Therefore, by determining which of the quadrature Doppler signals leads the other it is possible to determine whether the reflected sensor beam light is Doppler shifted up or down. The direction of motion of the intruder is towards or away from the source of the sensor beams if the frequency of the reflected sensor beam light is Doppler shifted respectively up or down.

According to an aspect of some preferred embodiments of the present invention a vertical cavity surface-emitting laser (VCSEL) is used to provide light in an intruder detection system. These lasers are relatively inexpensive, efficient sources of laser light having coherence lengths suitable for detecting intruders at distances required for many intruder detection applications.

In preferred embodiments of the invention VCSELs are used in systems with quadrature detection. However, quadrature detection requires knowing the direction of polarization of laser light provided by the laser and the polarization direction of light emitted by a VCSEL is known to "jump" from one to the other of two orthogonal polarization direction. Therefore, in preferred embodiments of the present invention using quadrature detection and a VCSEL, light emitted by the VCSEL is monitored so that its direction of polarization is known when quadrature detection measurements are performed.

An aspect of some preferred embodiments of the present invention relates to providing a system, hereinafter referred to as a “sentinel system” for protecting a valuable object, such as for example, a painting or artifact in a museum, against theft.

Laser intruder detection systems, in accordance with preferred embodiments of the present invention, provide sensitive discrimination between various different forms and magnitudes of motion. As a result, such detection systems are well suited for use as sentinel systems. They are capable of distinguishing everyday motions and vibrations of an object from motion indicating the object is being purloined and thereby can provide reliable protection of an object with a relatively low rate of false alarms. Furthermore, for a delicate artifact or objects subject to damage by vibration they can be used to sound an alarm if vibrations of the object reach an intensity or rate of occurrence that is liable to damage the object.

BRIEF DESCRIPTION OF FIGURES

The invention will be more clearly understood by reference to the following description of preferred embodiments thereof read in conjunction with the figures attached hereto. In the figures identical structures, elements or parts which appear in more than one figure are labeled with the same numeral in all the figures in which they appear. Dimensions of components and features shown in the figures are chosen for convenience and clarity of presentation and are not necessarily shown to scale. The figures are listed below.

Fig. 1 schematically shows a laser intruder detection system detecting an intruder, in accordance with a preferred embodiment of the present invention;

Fig. 2A schematically shows a laser intruder detection system, which uses quadrature detection, detecting an intruder, in accordance with a preferred embodiment of the present invention;

Fig. 2B schematically shows an optical module for determining the polarization direction of laser light used in the intruder detection system shown in Fig. 2A, in accordance with a preferred embodiment of the present invention;

Fig. 3 shows a block diagram of a circuit, in accordance with a preferred embodiment of the present invention, used to process signals in the laser detection system shown in Fig. 2;

Fig. 4 schematically shows a laser detection system protecting a room in accordance with a preferred embodiment of the present invention; and

Fig. 5 schematically shows a laser detection system being used as a sentinel system to protect a valuable picture, in accordance with a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 schematically shows a laser detection system 20 detecting the presence of an intruder 22 in a surveillance zone (the boundaries of which are not indicated in Fig. 1). Detection system 20 comprises a laser 24, two photo-detectors 26 and 28 and a diffractor 30. A controller 31 controls laser 24 and receives output signals from photo-detectors 26 and 28 generated responsive to light incident on the photo-detectors.

Laser 24 preferably has a coherence length substantially equal to twice a maximum distance for which intruders are to be detected. For example, if it is desired to detect intruder 22 at a distance of five meters, laser 24 preferably has a coherence length that is equal to or greater than ten meters. Preferably laser 24 radiates infrared light, for example light having a wavelength of 850nm or 980nm. For many intruder detection applications a power rating of approximately 1 milliwatt for laser 24 is sufficient. Preferably, laser 24 is a vertical cavity

surface emitting laser (VCSEL) that is operated in single-mode in order to obtain a required coherence length.

Laser light, represented by bold arrowed lines 32, is radiated by laser 24 and is collimated by a collimating lens 34. The light is directed so that it is incident on a surface 36 of diffractor 30. Some of laser light 32 is back-diffracted from surface 36 and some is transmitted through surface 36 and forward diffracted by diffractor 30. Preferably surface 36 is coated with an appropriate metallic or dielectric layer (not shown) that determines the ratio of the amount of incident laser light 32 that is back-diffracted to the amount of incident laser light 32 that is forward diffracted. Preferably only a small portion of incident laser light 32 is back-diffracted. In some preferred embodiments of the present invention diffractor 30 comprises an amplitude grating that diffracts laser light 32 by modulating the amplitude of incident laser light 32. In some preferred embodiments of the present invention diffractor 30 comprises a phase grating that diffracts laser light 32 by modulating the phase of incident laser light 32.

Some of the light that is back-diffracted by diffractor 30 is diffracted into beams of laser light, represented by dashed arrowed lines 40 and 42, that are directed towards photo-detectors 26 and 28 respectively. Beams of laser light 40 and 42 are reference beams of intruder detection system 20 and light from these reference beams are focused onto spots (not shown) on photo-detectors 26 and 28 respectively by lenses 44 and 46. Preferably, photo-detectors 26 and 28 are protected by irises 48 and 50 respectively that have openings, preferably, approximately the size of spots to which light in reference beams 40 and 42 is focused on photo-detectors 26 and 28. Irises 48 and 50 reduce the amount of background light incident on photo-detectors 26 and 28. In addition, photo-detectors 26 and 28 are preferably shielded by filters (not shown) that transmit substantially only light having a wavelength the same as that of laser light 32.

In some preferred embodiments of the present invention, photo-detectors 26 and 28 are small and do not require irises 48 and 50. The use of small photo-detectors, in accordance with a preferred embodiment of the present invention, can be advantageous because it simplifies construction. In addition smaller photo-detectors generally have smaller capacitance and dark currents than larger photo-detectors, both of which attributes improve signal to noise.

A portion (not shown) of laser light 32 that is back-diffracted by diffractor 30 is directed towards laser 24 and is incident on laser 24. While this is generally undesirable, the intensity of light back-diffracted to laser 24 is relatively low and it does not significantly degrade the performance of laser 24. Preferably, laser 24 is protected from light reflected back to laser 24 by a quarter wave plate and polarizer that prevent light reflected from diffractor 30

from reaching laser 24. In preferred embodiments of the present invention, in which the laser 24 is a VCSEL laser, the high reflectivity mirror of the laser also protects the laser from reflected light.

Laser light that is transmitted by diffractor 30 is diffracted into multiple sensor beams of laser light represented by arrowed lines 50, 51 and 52. Sensor beams 50, 51 and 52 extend into the volume of the surveillance zone protected by intruder detection system 20. Reference and sensor beams 40, 42, 50, 51 and 52 are coherent with each other.

Intruder 22 is shown, by way of illustrative example, illuminated by sensor beam 51 and moving towards diffractor 30 with a velocity "V_I" represented by double arrow 60. Light, represented by wavy arrows 62, from sensor beam 51 is reflected by intruder 22 back towards diffractor 30 where it is forward-diffracted towards photo-detectors 26 and 28. Reflected light 62 is focused onto photo-detectors 26 and 28 by the same lenses 44 and 46 respectively that focus reference beams 40 and 42 on photo-detectors 26 and 28. (Some of reflected laser light 62 is also forward-diffracted towards laser 24, however as a result of its relatively low intensity, the forward-diffracted light reaching laser 24 does not practically affect the laser's performance.)

Preferably, diffractor 30 is designed so that the spatial configuration of the sensor laser beams is a mirror image of the spatial configuration of reference laser beams. The reference and sensor laser beams of intruder detection system 20 have mirror image spatial configurations. However, in Fig. 1 a reference beam which is a mirror image of sensor beam 51 is not shown in the interests of simplicity of presentation. The back-diffracted "reference" beam not shown is a beam that back reflects to the laser, which is not used as a reference beam. As a result of the mirror image configurations, light reflected by an intruder from any of sensor beams 50, 51 or 52 is accurately focused to the same locations on photo-detectors 26 and 28 to which light in reference beams 40 and 42 is focused.

When reflected light 62 reaches photo-detector 26, photo-detector 26 generates a signal responsive to the energy received from both reflected light 62 and from reference beam light 40. Similarly, when reflected light 62 reaches photo-detector 28, photo-detector 28 generates a signal responsive to the sum of energy received from reflected light 62 and from reference beam light 42. The output signals from both photo-detectors comprise Doppler shift components, *i.e.* Doppler signals, that are in phase with each other and proportional to $\cos(2\omega_0 V_I t/c + \phi) = \cos(\omega_D t + \phi)$. In the formula, ω_0 is the frequency of laser light 32, c is the velocity of light, ϕ is a phase angle generated by a difference in optical path length to photo-

detectors 26 and 28 for reference beam light 40 and 42 respectively and reflected light 62, ω_D is the Doppler frequency shift in reflected light 62 caused by V_I and t is time.

It should be realized that only reflected light 62 that is incident on areas of photo-detectors 26 and 28 on which light from reference beams 40 and 42 is incident contributes to a Doppler signal. Reference beam light and reflected beam light that are incident on different areas of photo-detectors 26 or 28 contribute only to DC components of signals generated by photo-detectors 26 and 28.

To assure proper overlapping of intruder reflected light and reference light on photo-detectors 26 and 28, the diffraction angle of laser light 32 should preferably be less than the dispersion angle of reflected light 62. If α is the diffraction angle of laser light 32, $\alpha = k\lambda/W$ where λ is the wavelength of laser light 32, W is the beam width of collimated laser light 32 and k is a geometrical coefficient depending upon the shape of the collimated beam. If β is the dispersion angle of reflected light 62 reaching photo-detectors 26 and 28 then $\beta = W/L$, where L is the distance of intruder 22 from diffractor 30. Therefore, to assure proper overlap, preferably $\beta > \alpha$, which leads to a condition that preferably $W > (k\lambda L)^{1/2}$. By way of example, for $\lambda = 850$nm and L = 4 meters W should be greater than about 2 mm.

The output signals generated by photo-detectors 26 and 28 are transmitted to controller 31 where they are processed using methods known in the art to determine their component Doppler signals and the Doppler frequency ω_D. Preferably, ω_D is determined from a sum of output Doppler signals from photo-detectors 26 and 28. In some preferred embodiments of the present invention the outputs of photo-detectors 26 and 28 are electrically connected together before they are input to controller 31 in order to sum their Doppler signals. By using a sum of Doppler output signals, signal to noise is increased and accuracy of a determined value for ω_D improved.

In order to improve signal to noise, in some preferred embodiments of the present invention, one or more reference beams in an intruder detection system are focused onto preferably a same region of a single photo-detector using an appropriate combination of prisms, mirrors and/or common optical components. Intruder reflected light that is diffracted to coincide with the reference beams is therefore also focused to the same area on the photo-detector. A single photo-detector therefore collects and heterodynes reference light and reflected light that would otherwise be collected and heterodyned by at least two photo-detectors.

If ω_D has a value in a range of expected values for an intruder, controller 31 generates a signal to initiate an action appropriate to a purpose for which intruder detection system 20 is being used, for example to trigger an alarm, open a door or turn on an air conditioner. In Fig. 1 intruder detection system is shown triggering an alarm 33 when intruder 22 is detected.

In some preferred embodiments of the present invention diffractor 30 is cyclically moved back and forth in directions indicated by double arrowhead line 70. The direction and magnitude of velocity of diffractor 30 are sensed by controller 31 and correlated with measurements of Doppler frequencies to determine a direction of motion of intruder 22. There are many and varied methods, in accordance with preferred embodiments of the present invention for moving diffractor 30 back and forth and correlating motion of the diffractor with Doppler frequency measurements. For example, in a preferred embodiment of the present invention, a piezoelectric motor is used to move diffractor 30 back and forth along double arrowhead line 70. The piezoelectric motor is controlled to move diffractor 30 with a substantially constant accurately controlled velocity in a "forward" direction along double arrowed line 70 from a suitable first position to a second position. When diffractor 30 reaches the second position the piezoelectric motor is controlled to rapidly snap diffractor 30 back to the first position and begin the cycle again. Controller 31 monitors the motion cycle using methods known in the art, and Doppler shift measurement are made during times that diffractor 30 is being moved with the accurately controlled velocity in the forward direction. Alternatively, by way of another example, diffractor 30 may be moved back and forth harmonically and phases of the harmonic motion correlated with Doppler frequency measurements.

The motion of diffractor 30 does not affect the frequency of reflected light 62 however it does Doppler shift the frequency of reference beam light 40 and 42 incident on photo-detectors 26 and 28. Assume for example that diffractor 30 is moving towards laser 24 with a velocity V_d when reflected light 62 and reference beam light 40 and 42 are heterodyned by photo-detectors 26 and 28 respectively. If intruder 22 is not moving, Doppler signals from photo-detectors 26 and 28 are proportional to $\cos(2\omega_o V_d t/c + \phi)$ and a Doppler frequency ω_D for the Doppler signals will be determined to be equal to $\omega_d = 2\omega_o V_d/c$. If intruder 22 has a component of velocity V_I in a same or opposite direction as V_d, the Doppler frequency ω_D will be determined to have a value equal to $2\omega_o(|V_d| - |V_I|)$ or $2\omega_o(|V_d| + |V_I|)$ respectively. Thus, if intruder 22 is moving in a same direction as V_d (*i.e.* V_I and V_d are in the same direction), the Doppler frequency ω_D is less than ω_d and if intruder 22 is moving in a direction

opposite to V_d (*i.e.* V_I and V_d are in opposite directions), ω_D is greater than ω_d. To insure discrimination between motion of an intruder towards and away from diffractor 30, preferably, $|V_d|$ is chosen sufficiently larger than the magnitudes of velocities that characterize motion of an intruder so that $(|V_d| - |V_I|)$ is greater than zero for substantially all intruder velocities V_I. Therefore, in accordance with a preferred embodiment of the present invention, controller 31 determines the direction of V_I using a known direction and magnitude for V_d and a value determined for the Doppler frequency ω_D.

Intruder detection system 20 is shown with only two photo-detectors and associated reference beams and only three sensor laser beams for clarity of exposition. Intruder detection systems, in accordance with preferred embodiments of the present invention can have a number of photo-detectors and associated reference laser beams other than two and a number of sensor laser beams other than three. In many situations, it may be necessary or desirable for an intruder detection system, in accordance with a preferred embodiment of the present invention, to have more or less than three sensor beams to protect the volume of a particular surveillance zone. A diffractor required for practically any desired number of photo-sensors and number and spatial pattern of reference and sensor beams for an intruder detection system, in accordance with a preferred embodiment of the present invention, can be provided using techniques, such as holographic techniques, that are well known in the art.

It should also be noted that while the various laser beams comprised in intruder detection system 20 are indicated as being coplanar, intruder detection systems, in accordance with a preferred embodiment of the present invention comprising non-coplanar sensor and/or reference beams are possible and can be advantageous. Various two dimensional diffractors for diffracting a laser beam into a desired non-coplanar pattern of laser beams are well known in the art. Such two-dimensional diffractors can be used, in accordance with preferred embodiment of the present invention, to provide desired patterns of reference and sensor beams for protecting the volume of a surveillance zone.

In some cases where a sensor beam configuration comprising many sensor beams is required to provide protection for a surveillance zone, a single laser might not be able to provide sufficient energy for all the sensor beams. Therefore in some intruder detection systems, in accordance with preferred embodiments of the present invention, a plurality of lasers is used to provide a desired configuration and intensity of reference and sensor beams.

For example, consider an intruder detection system, in accordance with a preferred embodiment of the present invention, comprising first and second lasers, a linear diffractor having a grating pitch Λ and a collimating lens for focusing laser light on the diffractor.

Assume that the lasers are positioned along the intersection line of the focal plane of the collimator lens and a plane perpendicular to the diffractor grating lines that contains the optic axis of the collimating lens. Let the position of a laser be defined by an angle β that the optic axis of the laser makes with the optic axis of the collimator lens. Then if α_n (where n is an integer) is the angle of the n-th grating order for light radiated by the laser, $\sin(\alpha_n) + \sin(\beta) = n\lambda/\Lambda$, where λ is the wavelength of light radiated by the laser.

If the first laser is located on the optic axis of the collimating lens (as is the case for intruder detection system 20 of Fig. 1), then $\beta = 0$ and the grating orders occur at angles $\alpha_n = n\lambda/\Lambda$. Assume the second laser is positioned at an angle $\beta = \sin^{-1}(\lambda/2\Lambda)$. The grating orders for the second laser occur at angles α_n for which $\sin(\alpha_n) = (n-1/2)\ \lambda/\Lambda$.

The grating angles for the second laser therefore occur substantially midway between the grating angles of the first laser. The addition of the second laser, in accordance with a preferred embodiment of the present invention, therefore doubles the number of reference and sensor beams in the intruder detection system without the need to decrease the intensity of individual reference and sensor beams.

As another example, consider that an intruder detection system, in accordance with a preferred embodiment of the present invention, comprises a plurality of lasers that emit light of different wavelengths. Assume that the i-th laser emits light having a wavelength λ_i and that the i-th laser is located at an angle $\beta_i = \lambda_i/(2\Lambda)$ (using the same coordinate conventions as in the last example). The i-th laser will then generate a pattern of reference and sensor beams defined by grating angles $(n-1/2)\lambda_i/\Lambda$. While the configurations of reference and sensor beams for all the lasers are similar, since the wavelengths λ_i are all different, the configurations are shifted one from the other and do not in general overlap. If there are a total of N lasers, the intruder detection system will comprise N distinct non-overlapping reference and sensor beam configurations, each powered by its own laser and each characterized by a different wavelength of light.

The use of different wavelengths in an intruder detection system in accordance with a preferred embodiment of the present invention can be advantageous. Clothes worn by an intruder might for example reflect light of one wavelength weakly and light of a second wavelength strongly or ambient light might reduce signal to noise in one wavelength but not in another.

In some preferred embodiments of the present invention, a non-planar spatial configuration of reference and sensor beams is provided by forming a laser intruder detection

system from sub-units, each of which is a laser detection system that provides a planar distribution of reference and sensor beams. For example, a laser intruder detection system may comprise a plurality of sub-units each of which is a laser detection system 20 shown in Fig.1. The sub-units may for example be "stacked" one on top of the other with the planes of their respective sensor beams 50, 51 and 52 (Fig. 1) parallel or tilted with respect to each other to form various wedge shaped configurations of sensor beams.

Whereas, as noted above, almost any "static" pattern of sensor beams, in accordance with a preferred embodiment of the present invention, required to protect a surveillance zone can be provided, it may be desirable or advantageous to scan a surveillance zone with a pattern of sensor beams. Therefore, in some preferred embodiments of the present invention, a spatial configuration of sensor beams is moved to scan the volume of a surveillance zone. For example, components of intruder detection system 20 may be mounted in an appropriate housing that is mechanically rotated about at least one axis or translated along at least one axis to move sensor beams 50, 51 and 52 and thereby scan the volume of a surveillance zone protected by intruder detection system 20.

Fig. 2A schematically shows another intruder detection system 100, detecting the presence of intruder 22 in a surveillance zone protected by intruder system 100, in accordance with a preferred embodiment of the present invention. Intruder detection system 100 is similar to intruder detection system 20 shown in Fig. 1. However, intruder detection system 100 is designed to determine a direction of motion of intruder 22 using quadrature detection.

Intruder detection system 100 comprises a laser 24 that emits laser light 32 and two photodetectors 26 and 28. A linear polarizer 102 and an iris 48 are positioned in front of photo-detector 26 and a linear polarizer 104 and an iris 50 are positioned in front of photo-detector 28. Preferably, the polarization transmission axes of polarizers 102 and 104 are orthogonal. (A polarization transmission axis of a polarizer is defined as a direction in the polarizer that is parallel to the polarization vector of light that passes through the polarizer.) As in the case of intruder detection system 20, if photo-detectors 26 and 28 of intruder detection system 100 are sufficiently small, irises 48 and 50 are not necessary. Preferably photo-detectors 26 and 28 are protected by appropriate filters that transmit substantially only light having a wavelength the same as that of laser light 32.

Laser light 32 from laser 24 is collimated by a lens 106 and back and forward-diffracted by a diffractor 30. Diffractor 30 is preferably a linear diffractor, which, in the perspective of Fig. 2 has grating lines perpendicular to the plane of Fig. 2. Surface 36 of diffractor 30 is preferably coated with an appropriate metallic or dielectric layer (not shown) to control the

ratio of the amount of light from laser light 32 that is back-diffracted to the amount of light from laser light 32 that is forward-diffracted.

In some preferred embodiments of the present invention, diffractor 30 comprises a binary reflecting amplitude grating in which the width and reflectivity of reflecting lines determines the power ratio of the diffracted beams and the ratio of energy in forward diffracted to back-diffracted light. In some preferred embodiment of the invention, the diffractor is a phase grating, such as a binary phase formed from plastic. The ratio of energy in back to forward diffracted light and the power ratio between diffracted orders is controlled by properly selecting diffraction groove shape and depth and the indices of refraction of materials used in the grating.

Back-diffracted light is diffracted into reference beams 40 and 42. Light in reference beams 40 and 42 is focused by lens 106 onto photodetectors 26 and 28 respectively. Light in reference beams 40 and 42 pass through linear polarizers 102 and 104 before being incident on photo-detectors 26 and 28 respectively. Forward-diffracted light passes through a quarter wave plate 140 and a linear polarizer 142 and form sensor beams 50, 51 and 52.

To understand the operation of intruder detection system 100 assume, by way of example, that laser 24 is positioned so that the polarization vector of laser light 32 is oriented at an angle of 45° with respect to the normal to the plane of Fig. 2. As a result, the polarization vectors of light in reference beams 40 and 42 are also substantially orientated at 45° with respect to the normal. Preferably, the polarization transmission axes of polarizers 102 and 104 are oriented at 45° with respect to the polarization vectors of light in reference beams 40 and 42 (*i.e.* parallel and perpendicular to the plane of Fig. 2). As a result, the intensity of reference beam light 40 on photo-detector 26 is substantially the same as the intensity of reference beam light 42 on photo-detector 28.

A pertinent direction associated with a component or feature of an element in Fig. 2A is shown by a rubric in a circular "cross-hair" icon connected to the feature or element by a line. A bold line is used to indicate a polarization transmission axis of a polarizer and a bold arrow indicates the direction of a polarization vector. Circular polarization is indicated by a circle with an arrowhead pointing anti-clockwise or clockwise to indicate respectively right or left hand circularly polarized light. Directions are shown relative to the perpendicular to the plane of Fig. 2A which is represented by a "12 o'clock line" in icon 120.

Icons 122, 124 and 126 show preferred directions of the polarization vectors of laser light 32 and light in reference beams 40 and 42 respectively. Icons 128 and 130 show the

orthogonal directions of the polarization transmission axes of polarizers 102 and 104 respectively.

Intruder 22 is illuminated, by way of example, by sensor beam 51 and reflects light 62 from sensor beam 51 toward diffractor 30. On its way to diffractor 30, reflected light 62, which is typically substantially randomly polarized after being reflected from intruder 22, passes through linear polarizer 142 and then through quarter wave plate 140. Quarter wave plate 140 and polarizer 42 together form a circular polarizer that circularly polarizes reflected light 62. After passing through quarter wave plate 140, reflected light 62 is circularly polarized, as indicated in icon 152. Circularly polarized reflected light 62 is then forward-diffracted by diffractor 30 and focused by lens 106 so that it passes through linear polarizers 102 and 104 and is incident on photo-detectors 26 and 28 respectively. Because the polarization transmission axes of polarizers 102 and 104 are orthogonal, the polarization vectors of reflected light 62 reaching photo-detectors 26 and 28 are orthogonal and reflected light 62 incident on photo-detector 26 is phase shifted by $\pi/2$ radians from reflected light 62 incident on photo-detector 28.

Assume that intruder 22 is moving in the surveillance zone with a component of velocity V_I, represented by double arrow 60, in a direction parallel to sensor beam 51. As in the case of intruder detection system 20, the movement of intruder 22 generates Doppler shifts in reflected light 62 that are used to detect the presence of intruder 22. However, because reflected light 62 incident on photo-detector 26 is phase shifted with respect to reflected light 62 reaching photo-detector 28, in accordance with a preferred embodiment of the present invention, Doppler signals generated by photo-detectors 26 and 28 are usable to determine directions of motion for intruder 22.

Let DS_{26} represent a Doppler signal from photo-detector 26 and DS_{28} a Doppler signal from photo-detector 28. Then $DS_{26} = A\cos(2\omega_o V_I t/c + \phi)$ and $DS_{28} = A\cos(2\omega_o V_I t/c + \phi + \pi/2)$, where ω_o is the frequency of laser light 32. (The amplitudes of DS_{26} and DS_{28} are substantially the same because of the 45^o angles between the polarization vector of laser light 32 and the polarization transmission axes of polarizers 102 and 104 and circular polarization of reflected light 62 which is incident on polarizers 102 and 104.)

DS_{26} and DS_{28} are a pair of quadrature signals. If V_I is positive, then DS_{26} is delayed by a quarter of a cycle with respect to DS_{28}. If V_I is negative, then DS_{26} leads DS_{28} by a quarter cycle. By determining which of signals DS_{26} and DS_{28} leads the other, the direction of V_I in accordance with a preferred embodiment of the present invention is determined.

It should be noted that the leading and lagging Doppler signals DS_{26} and DS_{28} are reversed if the polarization vector of laser light 32 is perpendicular to the choice of direction shown in Fig. 2. In order to determine a direction for V_I therefore it is necessary to know the direction of the polarization vector of laser light 32.

However, the polarization direction of light that some lasers radiate is not stable. For example, as noted above, the polarization direction of laser light from VCSEL lasers is apt to alternate between two orthogonal directions. In some preferred embodiments of the present invention therefore, the polarization direction of laser light 32 is monitored to determine a direction for its polarization vector. The determined direction is used by controller 31 in determining a direction for V_I.

The polarization of laser light 32 may be monitored, in accordance with preferred embodiments of the present invention, using different techniques and optical components known in the art. Fig. 2B schematically shows an optical module 170, which has components shown inside a dashed rectangle, that is used to monitor the polarization direction of laser light 32 in intruder detection system 100 shown in Fig. 2A, in accordance with a preferred embodiment of the present invention. In Fig. 2B only that portion of intruder detection system 100 necessary to describe the operation of module 170 is shown.

Module 170 preferably comprises a beam splitter 172, a linear polarizer 174 and a photo-detector 176. Beam splitter 172 is preferably positioned between laser 24 and lens 106 so that while light emitted by laser 24 passes through beam splitter 172 in order to reach lens 106, beam splitter 170 doesn't interfere with reference beams 40 and 42. Most of the light in laser light 32 incident on beam splitter 172 is transmitted by beam splitter 172 to lens 106 and preferably only small portion, represented by arrowed lines 173, is reflected towards linear polarizer 174. The polarization transmission axis of polarizer 174 is preferably oriented so that when laser light 32 is polarized along a first of its two orthogonal polarization directions, substantially all the light from laser light 32 reaching polarizer 174 from beam splitter 172 is transmitted to photo-detector 176. When laser light 32 is polarized along a second of its two orthogonal polarization directions, substantially no light from laser light 32 reaching polarizer 174 from beam splitter 172 is transmitted to photo-detector 176. The magnitude of the output of photo-detector 176 therefore indicates the polarization direction laser light 32.

The polarization directions of light and the directions of polarization transmission axes used to illustrate the operation of intruder detection system 100 are chosen for ease of presentation and other "polarization combinations" that would function to provide quadrature detection are possible and will occur to persons of the art. For example laser light 32 may be

circularly polarized and reflected light 62 polarized at 45°, *i.e.* laser light 32 and reflected light 62 "exchange roles".

Fig. 3 shows a block diagram of a circuit 200, in accordance with a preferred embodiment of the present invention, comprised in controller 31 for processing output signals from photo-detectors 26 and 28 in intruder detection system 100.

Circuit 200 comprises a processor 202 and signal-processing modules 204 and 206 that comprise components shown inside dashed rectangles labeled with the numeral of the module to which they belong. Signal processing module 204 receives signals 210 from photo-detector 28 and provides processed output signals responsive to received signals 210 to processor 202. Similarly signal-processing module 206 receives signals 212 from photo-detector 26 and provides processed output signals responsive to signals 212 to processor 202. Modules 204 and 206 are preferably identical and components and operation of only module 204 will be described.

An output signal 210 received by module 204 from photo-detector 28 is preferably first amplified by a preamplifier 214 and then filtered by a band-pass filter 216. Band-pass filter 216 removes DC components from signal 210 that are generated by light from reference beam 42 and ambient light. Preferably, band-pass filter 216 transmits only frequencies in a desired band of frequencies characteristic of Doppler shift frequencies generated by an intruder moving in a surveillance zone of intruder detection system 100. Frequency components of signal 210 transmitted by band-pass filter 216 are preferably amplified a second time by an amplifier 218 and input to a Schmitt trigger 220. Schmitt trigger 220 converts input from amplifier 218 to logic signals that are input to processor 202.

In accordance with a preferred embodiment of the present invention circuit 200 comprises a module 230 for processing output signals 232 from photo-detector 176, which is comprised in optical module 170 shown in Fig. 2B. As discussed above in the description of optical module 170, output signals from photo-detector 176 indicates a direction for the polarization of laser light 32 used in intruder detection system 100 (Fig. 2A). A signal 232 from photo-detector 176 is preferably amplified by an amplifier 234 and converted to a logic signal by a comparator 236, which logic signal is input to processor 202.

Processor 202 preferably processes signals from modules 204 and 206 using quadrature detection algorithms well known in the art, and polarization directions determined from signals from module 170, to determine magnitudes and directions of velocities from the signals. Processors that perform quadrature detection required by intruder detection systems, in accordance with preferred embodiments of the present invention, are readily available

commercially. A description of such commercially available processors and their mode of operation may be found in the Jan 1998 Honeywell Infrared Products catalogue pp. 407 – 412.

Preferably, processor 202 analyzes determined magnitudes and directions to determine if they are consistent with motion of an intruder in the surveillance zone or they represent stimuli that should be ignored. If they are consistent with motion of an intruder, circuit 200 generates a signal to initiate an appropriate response to the intruder, such as, if the intruder is unwelcome, sounding an alarm 240, or if the intruder is welcome, opening a door 242 or turning on an air conditioner 244.

Because intruder detection systems 20 (in versions that determine directions of velocities) and 100, determine both magnitudes and directions of velocities from signals generated by photo-detectors 26 and 28, intruder systems 20 and 100 are sensitive to differences between sources that stimulate signals in photodetectors 26 and 28. For example, intruder detection systems 20 and 100 can relatively easily discriminate between vibratory motion of objects and structures in a surveillance zone and steady motion in a particular direction characteristic of motion of an intruder. As a result, intruder detection systems in accordance with preferred embodiments of the present invention can provide reliable detection efficiencies with relatively low false alarm rates.

Fig. 4 shows a schematic plan view of an intruder detection system 250 protecting a room 252, having walls 254 and a door 256, in accordance with a preferred embodiment of the present invention. Laser light sensor beams 258 extend to span the volume of room 252 from a housing 255 comprising optical and electronic components (not shown) of detection system 250. Intruder detection system 250 can, for example, determine if door 256 is being opened or closed or if a person is moving in room 252 and generate signals to initiate appropriate responses thereto. It can also determine that signals that it receives are generated by vibrations in walls 254, which might for example be caused by the passage of a heavy vehicle in the vicinity of room 252, and "decide" to ignore the signals.

Intruder detection systems in accordance with a preferred embodiment of the present invention, because of their capability to differentiate between different patterns of motion are useable as "sentinel" security systems to guard valuables such as paintings or artifacts in a museum. Sentinel security systems, in accordance with preferred embodiments of the present invention, may also be used to protect cars against theft.

Fig. 5 shows an intruder detection system, in accordance with a preferred embodiment of the present invention, being used as a sentinel system 260 to guard a valuable painting 262 hung on wall 264. Sentinel system 262 comprises a housing 266 from which preferably a

plurality of relatively closely spaced sensor beams 268 are emitted. Sensor beams 268 are incident on picture 262. Normal vibrations of picture 262, such as caused by people walking past picture 262 and air drafts moving through the room are detected by sentinel system 266 and ignored. However, if a thief were to attempt to remove the painting from wall 264, sentinel system 268 would determine that movement of picture 262 is anomalous and would sound an alarm. It should be realized that whereas sentinel system 260 illuminates picture 262 with a plurality of sensor beams 268 in some sentinel systems, in accordance with preferred embodiments of the present invention a single sensor beam is used to guard an object.

In the description and claims of the present application, each of the verbs, "comprise" "include" and "has", and conjugates thereof, are used to indicate that the object or objects of the verb are not necessarily a complete listing of components, elements or parts of the subject or subjects of the verb.

The present invention has been described using non-limiting detailed descriptions of preferred embodiments thereof that are provided by way of example and are not intended to limit the scope of the invention. Variations of embodiments described will occur to persons of the art. The scope of the invention is limited only by the following claims.

CLAIMS

1. An intruder detection system for detecting an intruder in a surveillance zone comprising:

at least one laser that produces laser light;

at least one photodetector that generates signals responsive to light incident thereon;

a light distributor that receives laser light from the at least one laser and distributes the light into the surveillance zone and at least one laser beam, which does not extend into the surveillance zone, that is incident on the at least one detector; wherein light reflected by the intruder from the surveillance zone is incident on the diffractor and diffracted thereby so that reflected light is incident on the at least one photodetector; and

circuitry that receives signals generated by the at least one photodetector and determines whether a received signal comprises a component generated responsive to a Doppler shift in the frequency of light incident on the photo-detector from the surveillance zone and if the reflected light is Doppler shifted by motion of an intruder, the circuitry generates a signal indicating the intruder's presence in the surveillance zone.

2. An intruder detection system according to claim 1 wherein a surface of the distributor on which light from the laser is incident comprises a partially reflecting layer that controls the ratio of the amount of light sent to the sensors to the amount of light that is transmitted to the surveillance zone.

3. An intruder detection system according to claim 2 wherein the at least one beam that is incident on the at least one photo-detector is formed by light that is back distributed by the distributor.

4. An intruder detection system according to claim 3 wherein the at least one back distributed beam comprises a plurality of back distributed beams.

5. An intruder detection system according to any of the preceding claims wherein the light distributed into the surveillance zone comprises a plurality of forward beams.

6. An intruder detection system according to claim 5 wherein each forward distributed beam that extends into the surveillance zone has a mirror image back distributed beam.

7. An intruder detection system according to claim 6 wherein the at least one photodetector comprises a plurality of photodetectors.

8. An intruder detection system according to claim 7 wherein a single back distributed beam is incident on each photodetector.

9. An intruder detection system according to any of claims 1 - 8 wherein if a signal from a photodetector comprises a component generated responsive to a Doppler shift frequency in light incident on the photodetector, the circuitry determines a value for the Doppler-shift frequency.

10. An intruder detection system according to claim 9 comprising a motor that cyclically moves the diffractor back and forth in a direction so as to Doppler shift the frequency of light in back diffracted beams by a predetermined frequency shift.

11. An intruder detection system according to claim 10 comprising an optical frequency shifter through which light reflected from forward diffracted beams that is incident on at least one of the plurality of photodetectors passes, which optical frequency shifter generates a predetermined frequency shift in the frequency of the reflected light.

For the Applicant

Fenster & Co. Patent Attorneys, Ltd.

ABSTRACT

An intruder detection system for detecting an intruder in a surveillance zone comprising:

at least one laser that produces laser light;

at least one photodetector that generates signals responsive to light incident thereon;

a light distributor that receives laser light from the at least one laser and distributes the light into the surveillance zone and at least one laser beam, which does not extend into the surveillance zone, that is incident on the at least one detector; wherein light reflected by the intruder from the surveillance zone is incident on the diffractor and diffracted thereby so that reflected light is incident on the at least one photodetector; and

circuitry that receives signals generated by the at least one photodetector and determines whether a received signal comprises a component generated responsive to a Doppler shift in the frequency of light incident on the photo-detector from the surveillance zone and if the reflected light is Doppler shifted by motion of an intruder, the circuitry generates a signal indicating the intruder's presence in the surveillance zone.

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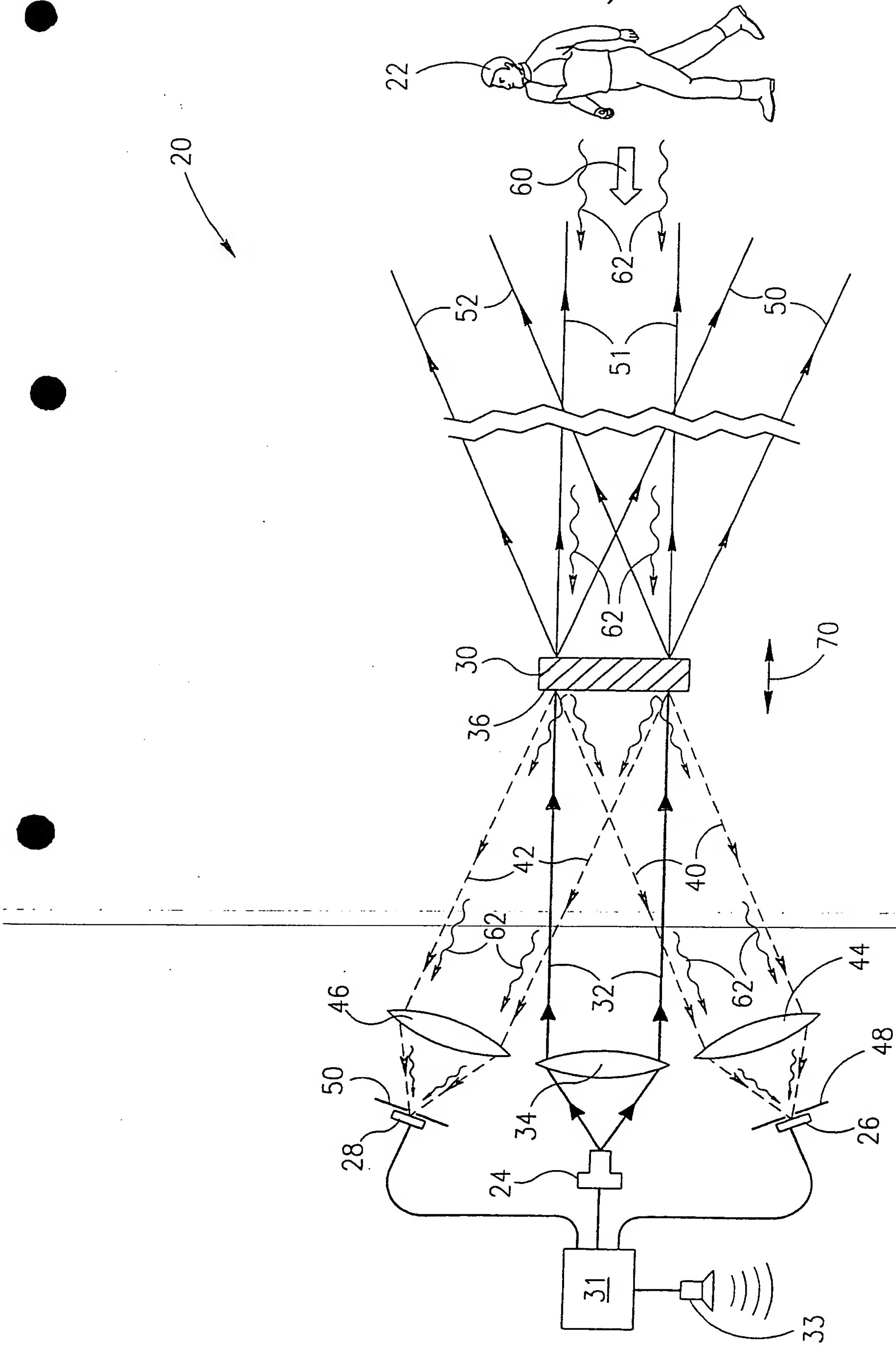

FIG.1

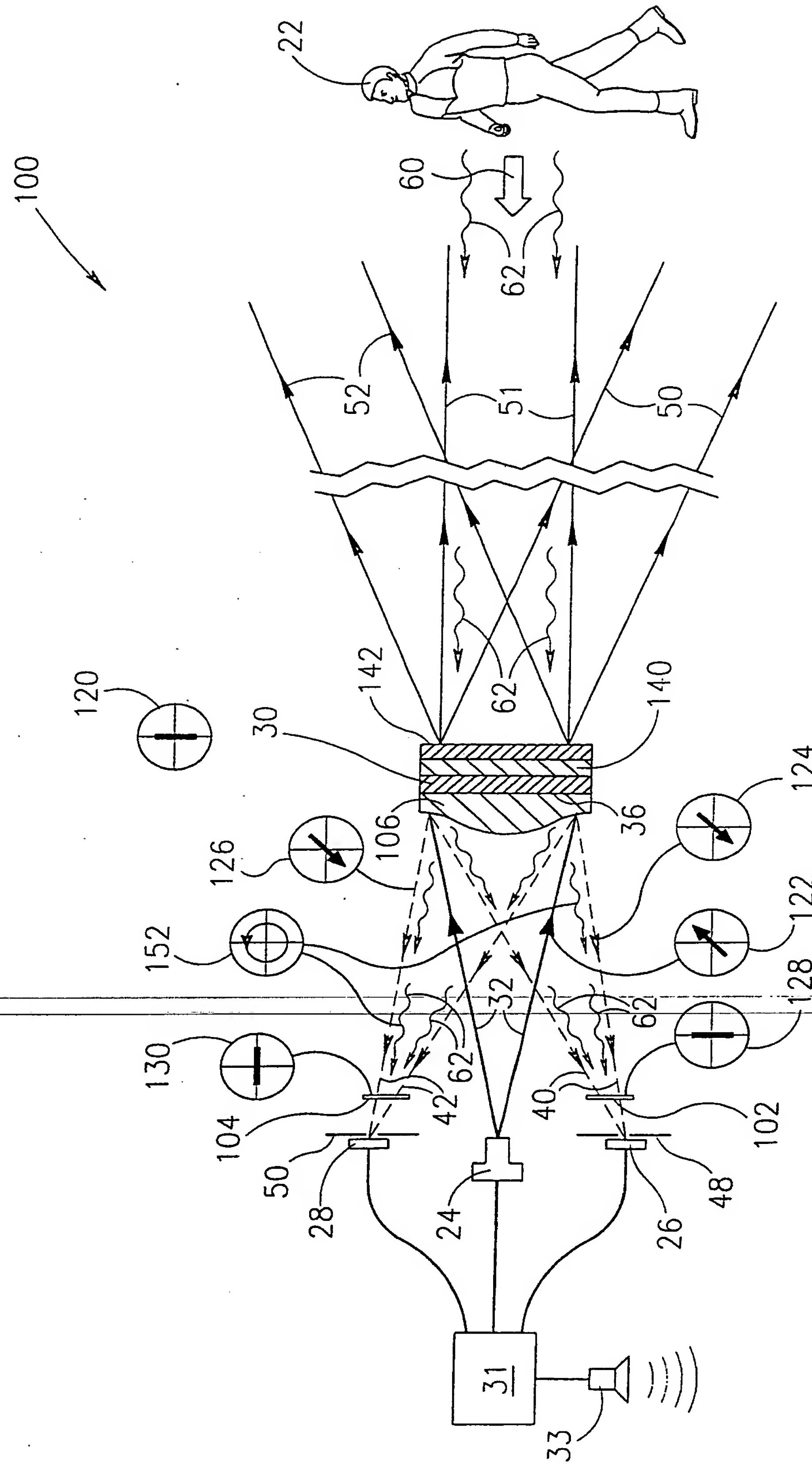

FIG.2A

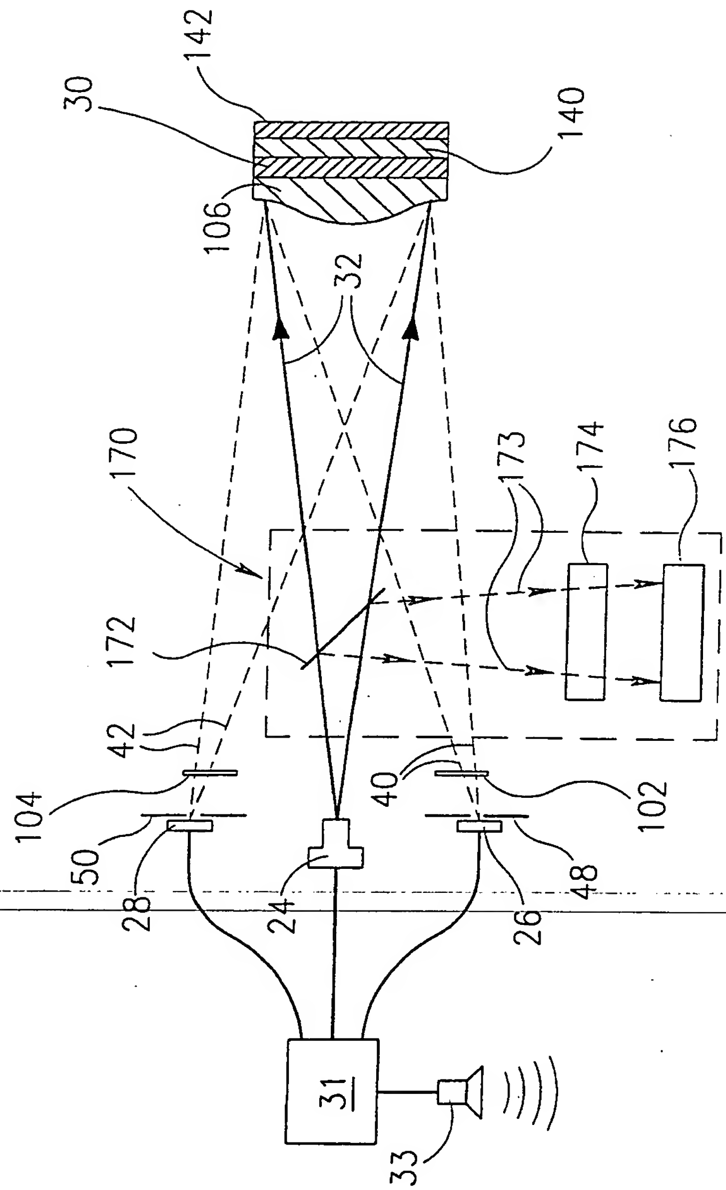
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FIG.2B

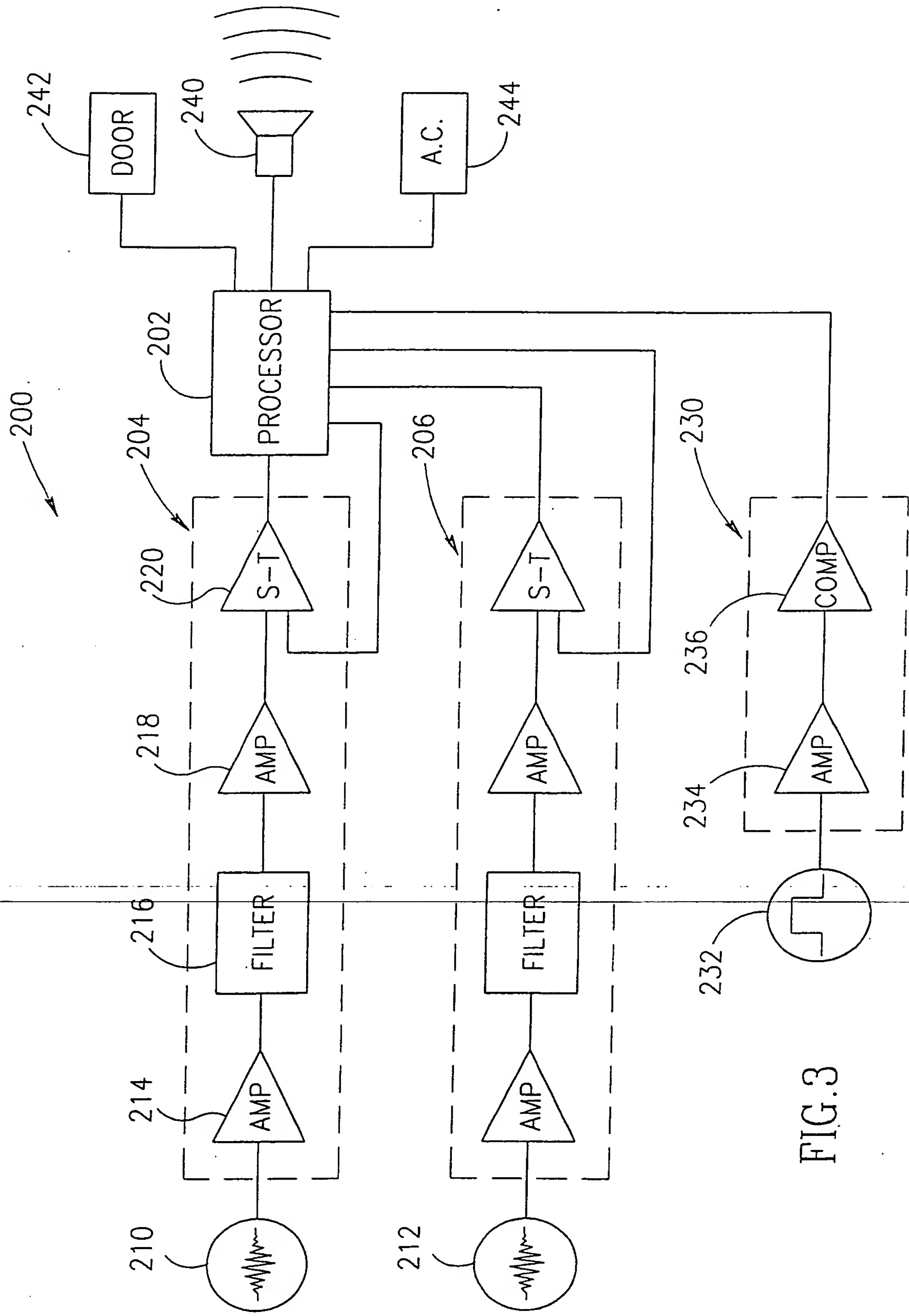
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FIG.3

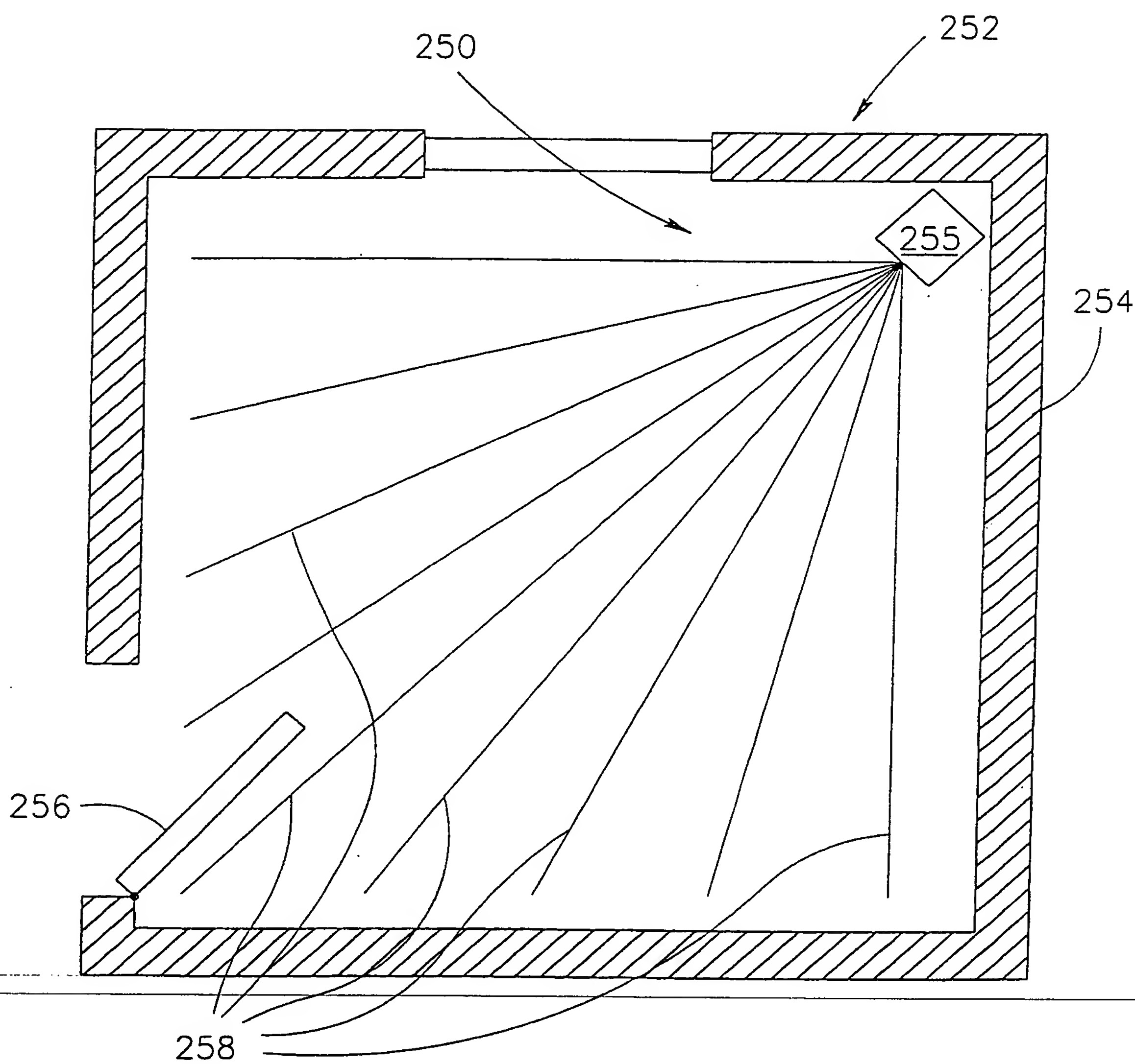

FIG.4

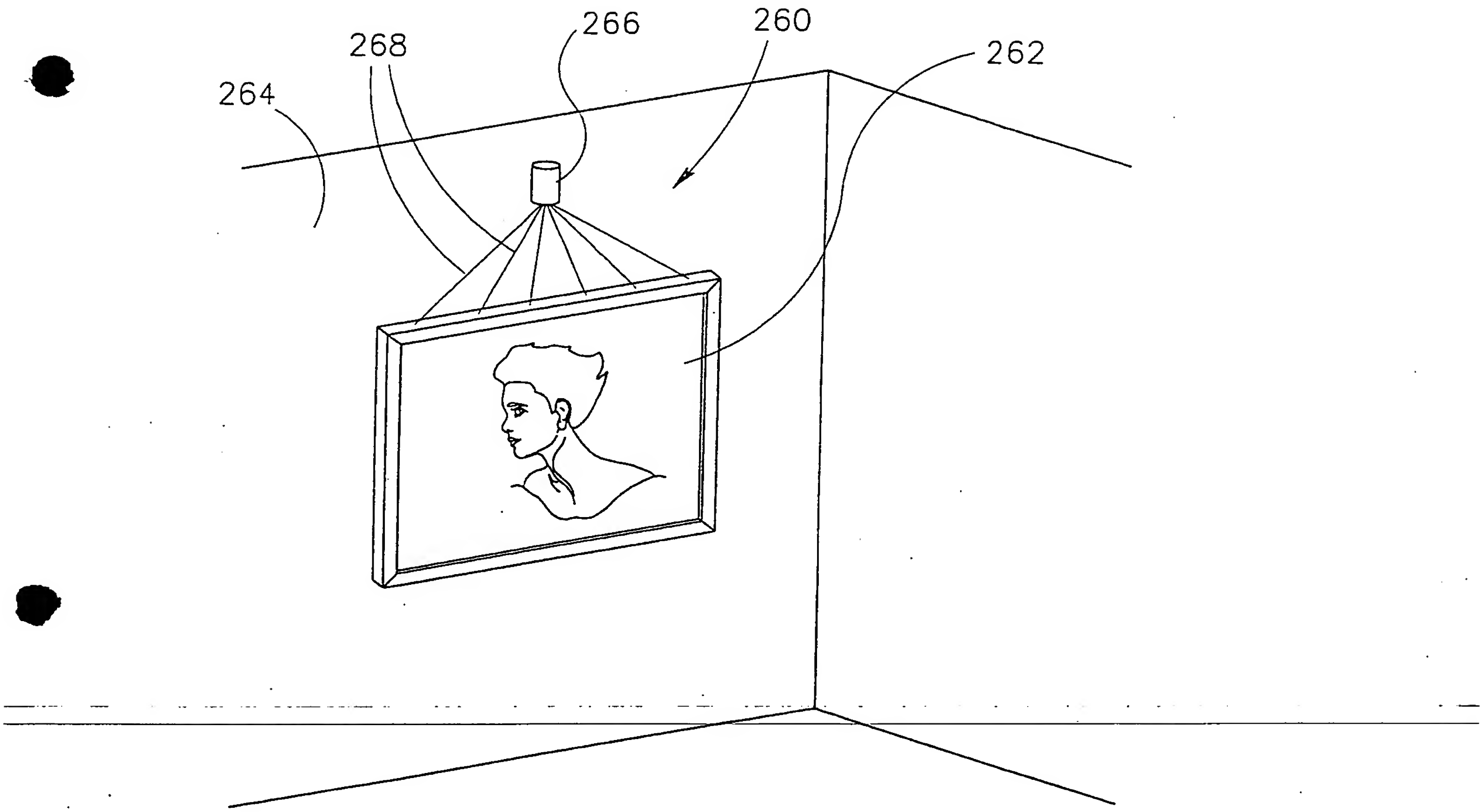

FIG.5